On-orbit Experiments and Applications of Shape Memory Alloy Mechanisms

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ABSTRACT

Spacecraft require a variety of mechanisms to accomplish mission-related functions such as deployment, articulation, and positioning. Current off-the-shelf devices such as pyrotechnic separation nuts, paraffin actuators, and other electro-mechanical devices may not be able to meet future satellite requirements, such as low shock and vibration, and zero contamination. The Air Force Research Laboratory (AFRL), with corporate and government partners, has developed Shape Memory Alloy (SMA) spacecraft release mechanisms and hinges as alternatives. In order to meet future goals, the SMA devices have been designed to reduce shock and vibration, reduce parts, and eliminate pyrotechnics.

This paper will focus on descriptions and results of on-orbit SMA mechanism experiments and applications. AFRL has flown SMA release devices as part of the Shape Memory Alloy Release Device (SMARD) experiment on MightySat I. The SMARD experiment, that compared the shock and release times of two SMA devices with those of current off-the-shelf devices, was conducted in May 1999 with extremely successful results. In addition, four AFRL funded SMA release mechanisms successfully deployed the Air Force Academy FalconSat spacecraft from the Orbital Sub-Orbital Program Space Launch Vehicle (OSP-I) in January 00. AFRL has also conducted an on-orbit experiment with SMA hinges. The hinges were flown as part of the Lightweight Flexible Solar Array (LFSA) program, that was a joint AFRL/DARPA/NASA/Lockheed Martin program to develop innovative solar array technologies. Six SMA hinges were launched as part of the LFSA experiment on the Space Shuttle Columbia (STS-93) in July 1999 with successful results.

Keywords: Shape memory alloy, release device, hinge, solar array, MightySat I, FalconSat

1. INTRODUCTION

The Air Force Research Laboratory (AFRL) has been actively developing improved spacecraft mechanisms that employ Shape Memory Alloys (SMA). These mechanisms provide improvements over traditional devices in many respects, such as shock, safety, and simplicity. Two types of devices for which a need has been identified are spacecraft release mechanisms and hinges. Development efforts for SMA hinges and release devices have progressed from prototypes to on-orbit experiments, and, in the case of release devices, to actual satellite deployment.

For the release devices, the basic application of SMA technology is that of an actuator or trigger that replaces the traditional pyrotechnic charge. The goals are to reduce shock, and eliminate contamination and hazards associated with the explosives. The primary goal has been to design the devices as drop-in replacements for pyrotechnic mechanisms. For example, size, mass, and power requirements of the new devices should be comparable to those of the pyrotechnics. The AFRL has provided funding to Lockheed Martin Astronautics (LMA) and Starsys Research Corporation (SRC) for development and test of several SMA actuated release devices. By the end of the 1990's, design of the devices had advanced to the point where flight opportunities were being sought for experimentation and application. The two opportunities that arose were the AFRL MightySat I Shape Memory Alloy Release Device (SMARD) experiment, and the Air Force Academy FalconSat spacecraft. The FalconSat project is an actual satellite release application. The success of the first low-shock devices is expected to pave the way for numerous applications, such as picosats, large spacecraft release, and fairing and stage separation.

The AFRL has also been involved in the development of SMA hinges for deployment of solar array panels. In addition to its uses as an actuator for conventional mechanisms, the ability of an SMA to recover a parent shape naturally opens up the possibility of using the SMA material as a mechanism itself. A hinge that is essentially a piece of SMA material connecting

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14. ABSTRACT
Spacecraft require a variety of mechanisms to accomplish mission-related functions such as deployment, articulation, and positioning. Current off-the-shelf devices such as pyrotechnic separation nuts, paraffin actuators, and other electro-mechanical devices may not be able to meet future satellite requirements, such as low shock and vibration, and zero contamination. The Air Force Research Laboratory (AFRL), with corporate and government partners, has developed Shape Memory Alloy (SMA) spacecraft release mechanisms and hinges as alternatives. In order to meet future goals, the SMA devices have been designed to reduce shock and vibration, reduce parts, and eliminate pyrotechnics. This paper will focus on descriptions and results of on-orbit SMA mechanism experiments and applications. AFRL has flown SMA release devices as part ofthe Shape Memory Alloy Release Device (SMARD) experiment on MightySat I. The SMARD experiment, that compared the shock and release times of two SMA devices with those of current off-the-shelf devices, was conducted in May 1999 with extremely successful results. In addition, four AFRL funded SMA release mechanisms successfully deployed the Air Force Academy FalconSat spacecraft from the Orbital Sub-Orbital Program Space Launch Vehicle (OSP-I) in January 00. AFRL has also conducted an on-orbit experiment with SMA hinges. The hinges were flown as part of the Lightweight Flexible Solar Array (LFSA) program, that was a joint AFRL/DARPA/NASA/Lockheed Martin program to develop innovative solar array technologies. Six SMA hinges were launched as part of the LFSA experiment on the Space Shuttle Columbia (STS-93) in July 1999 with successful results.

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a deployable to a spacecraft can be designed to recover a deployed configuration on heating. A SMA hinge offers some compelling advantages over traditional hinges such as simplicity in design and construction, minimal parts, and low shock deployment. The AFRL has participated in a joint AFRL/DARPA/NASA/Lockheed Martin program known as Lightweight Flexible Solar Array (LFSA) which is providing opportunities to design and test SMA hinges for array deployment. These efforts led to the design of a hinge experiment conducted on STS-93 in July 1999 that successfully tested six SMA hinges for deployment rate characteristics. The next step is a planned experiment in April 2000 on NASA's Earth Observer 1 (EO-1) in which the hinges will be used to deploy solar array panels.

2. SMA RELEASE DEVICES - BACKGROUND

Spacecraft require a variety of release devices to accomplish mission-related functions such as separation from the launch vehicle and deployment of solar arrays and other appendages. The separation device has a dual purpose – to secure the payload against the launch loads and to release the payload on-orbit cleanly, at the appropriate time, while minimizing detrimental effects such as shock and contamination. In some cases, where more than one release device is used, the additional task of synchronous release becomes a factor in mission success.

Separation has typically been achieved through the use of pyrotechnic devices. Generally these devices meet many of the basic requirements for a separation device. They are able to secure the payload during launch and can provide a timely, synchronized release on-orbit. However, there are drawbacks to the pyrotechnic devices. The first is the cost of handling the pyrotechnic devices safely. Launch vehicle manufacturers have extensive, costly, safety standards for storage, transportation, and handling of pyrotechnics during ground operations and integration. For shuttle payloads, incorporation of pyrotechnics further increases the burden of compliance with a manned space flight safety program. The second problem with pyrotechnics is their impact on the payload upon release. Pyrotechnic devices generate high shock, on the order of thousands of g's, that can physically damage the payload, and can produce contaminants that are detrimental to lenses and electronics.

With the newest generation of nano and microsatellites, the issues of shock and contamination become even more critical. For satellites of this size, external and internal parts are physically closer to the source of shock and contamination than those on larger satellites of the past. In addition, multiple satellite or constellation launch schemes may subject an individual satellite to multiple release shocks prior to its own release. These new challenges, and the drawbacks mentioned above, are compelling motives for the investigation and development of new approaches to satellite separation.

The SMA release devices developed with AFRL funding are shown in Figures 1, 2, and 3. The Low Force Nut (LFN) and Two-Stage Nut (TSN), shown in Figures 1 and 2, were designed and built by LMA. Figure 3 shows a device known as the QWKNUT, which is designed and built by SRC. The AFRL provided funding to SRC to incorporate improvements in the QWKNUT and qualify the device for flight. All three are "separation nut" devices that hold and release a ¼-inch bolt. All devices are activated by heating an internal SMA actuator, which initiates a mechanical sequence and releases the bolt.

Figure 1. Low Force Nut
Lockheed Martin Astronautics

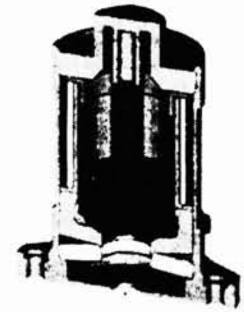

Figure 2. Two Stage Nut
Lockheed Martin Astronautics

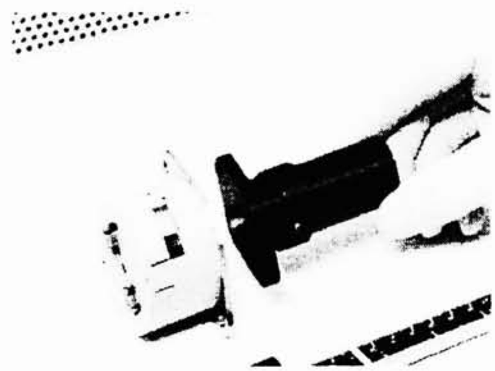

Figure 3. QWKNUT, Starsys Research Corporation

The devices are comparable to pyrotechnic ¼-inch bolt release devices regarding size, shape, and preload capability. However, the shock produced by each of the SMA devices is less than 500 g's, as compared to pyrotechnic devices that produce at least 7000 g's. The devices are all resettable. The TSN produces lower shock than the other two by employing a mechanism that relieves the preload on the bolt prior to release. The QWKNUT has a significantly lower power requirement than the LFN and TSN, which allows it to operate using the power typically supplied by launch vehicles for pyrotechnic release devices.

3.0 SMARD EXPERIMENT

3.1 Experiment Description

As part of the LFN and TSN development efforts, LMA designed the SMARD experiment to be flown on MightySat I. The objective of the experiment was not only to achieve the first on-orbit firing of the AFRL devices, but to prove that new alternative devices, comparable to pyrotechnics in size, mass, and release time, could function properly in the space environment, and provide significantly diminished shock.

In order to achieve an equal comparison between the new AFRL devices and traditional technologies, four devices were included in the SMARD experiment. These devices were the LFN and TSN, a Hi-Shear pyrotechnic device, and a linkwire device. The linkwire device is an existing release mechanism manufactured by G&H technology that employs neither pyrotechnics nor SMA. All of the devices are comparable in size and mass, and are designed to release a ¼-inch bolt. The general scheme of the experiment was to preload the devices to their maximum capacity prior to launch, and then fire them sequentially while on-orbit. For each device, the bolt preload and shock output was monitored before, during, and after firing. The shock output was measured by accelerometers. The bolt preload was monitored to indicate the time at which the bolt was released.

The experiment hardware consisted of an enclosure that contained the release devices and instrumentation, and a separate electronics box. The LFN and TSN were mounted on a common test fixture in the enclosure along with the linkwire and pyrotechnic devices, see Figure 4. The electronics box provided control of the experiment and regulation of the 28 VDC spacecraft power supply. The release devices were preloaded, with load cells installed to monitor the preload. Two accelerometers were also installed in the enclosure to measure the shock induced by each device. One low gain accelerometer and one high gain accelerometer were provided to cover the expected range of shocks. By inspecting the shock and preload data, the time at which the mechanism was actuated could be determined as well as the time at which the bolt was released. Temperature in the enclosure was also recorded.

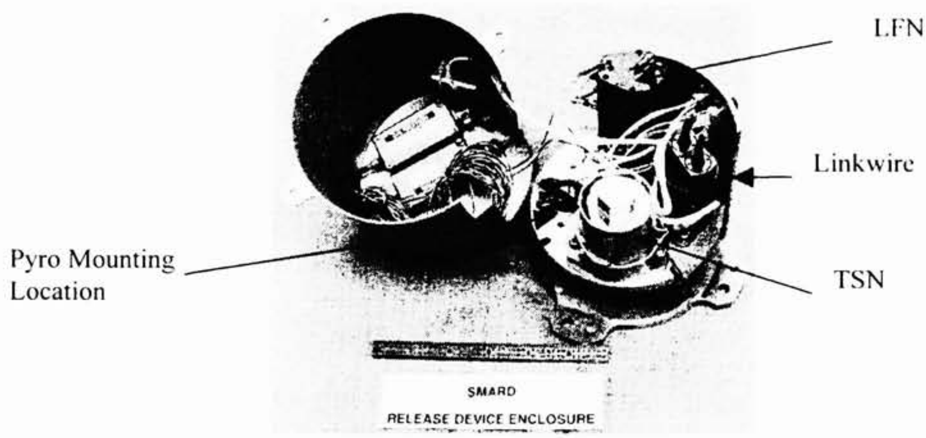

Figure 4. SMARD Experiment Enclosure with LFN, TSN, and Linkwire Installed

The experiment test goals were to fire each device and obtain the shock and preload data, for comparison purposes. The experiment would be considered completely successful if, as actually occurred, all four devices fired and all required data was collected. In that case, not only would the ability of the SMA devices to withstand the launch and space environment be proven, but a quantitative comparison of key parameters could also be made.

3.2 Data and Results

3.2.1 Ground Tests

Prior to launch of the experiment, ground tests were performed on the four release devices to establish a basis for comparison with on-orbit results and to establish the instrumentation and control required on-orbit. Figure 5 shows the shock response spectrum results from those tests for the four devices. It is important to note that the two SMA devices produced shocks significantly lower than the other two devices across the entire spectrum. The curve labeled "0.8 limit" is a maximum shock design goal that was established for the SMA devices. The SMA devices met this goal as well.

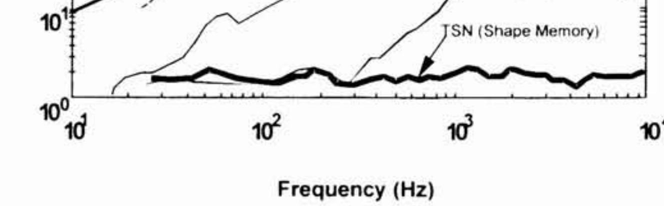

Figure 5. Ground Test Shock Response Spectra for Release Devices

3.2.2 On-orbit Results

A summary of shock responses from on-orbit firings is shown in Table 1.

Freq. / Device	100 Hz	500 Hz	1000 Hz	2000 Hz	3000 Hz	4000 Hz	6000 Hz
LFN	2	2	15	120	235	425	380
TSN	1	1	4	3	2	1	2
G&H	8	25	800	1700	2900	3400	4200
Pyro	30	400	2000	3200	5100	4800	6200

Table 1. On-orbit Shock Response of SMARD Devices.
Note: Shock is in g's.

The on-orbit shock response correlates well with the data from ground tests and clearly reveals that the LFN and TSN provide shocks significantly lower than the pyro or G&H linkwire device across the spectrum. In addition, the preload monitoring and accelerometer data were used to determine the release times as follows:

LFN: 62 ms
TSN: 22 ms
Linkwire: 15 ms
Pyrotechnic: 40 ms

The SMARD experiment was a complete success. All four of the devices fired successfully and returned the required data. Not only did the SMA devices survive launch, they survived for 6 months on-orbit before firing, thus establishing the robustness of the design. The data that was returned proved that the new low shock devices provide superior shock performance as compared to the traditional pyrotechnic and linkwire devices, while maintaining comparable release times.

4.0 AIR FORCE ACADEMY FALCONSAT RELEASE APPLICATION

Subsequent to development of the LFN and TSN with Lockheed Martin, the AFRL provided funding for additional work on SMA release devices to SRC. The device development research involved implementation of design improvements to the LFN and QWKNUT, and also had an application-oriented aspect. The AFRL had committed to providing low-shock release devices to the U.S. Air Force Academy for the FalconSat spacecraft, to be flown in on the first launch of the Orbital Sub-Orbital Program Space Launch Vehicle (OSP-I). This flight offered an opportunity for one of the release devices to be employed in a non-experimental release application.

The FalconSat spacecraft was designed with a discrete point mounting system that required four release devices. Since the QWKNUT was farther along in the design cycle than the LFN with regard to manufacturability, the QWKNUT was chosen for FalconSat. In May of 1999, the QWKNUT successfully underwent qualification testing for OSP-I and was integrated into the FalconSat separation system. Separation tests were performed at the Air Force Academy and at the AFRL after vibration tests. The separation system fired properly in three different tests. The integration itself was significant because it was the first time one of the AFRL supported devices was installed and test fired as part of a complete separation system.

In the launch configuration, FalconSat was mounted to a multiple satellite dispenser known as the Joint Air Force Academy-Weber State University Satellite (JAWSAT), using the four point separation system. The JAWSAT, that carried several other small satellites, was attached to the OSP-I launch vehicle using its own separation system. The JAWSAT is shown in Figure 6. It is important to note that because of the reset feature of the mechanism, the devices that flew were the same ones that were test fired with the separation system prior to integration. OSP-I was launched on 27 January 00. FalconSat was successfully released from JAWSAT in the correct orbit, approximately 15 minutes after arrival on-orbit. No problems or anomalies involving the separation system were detected.

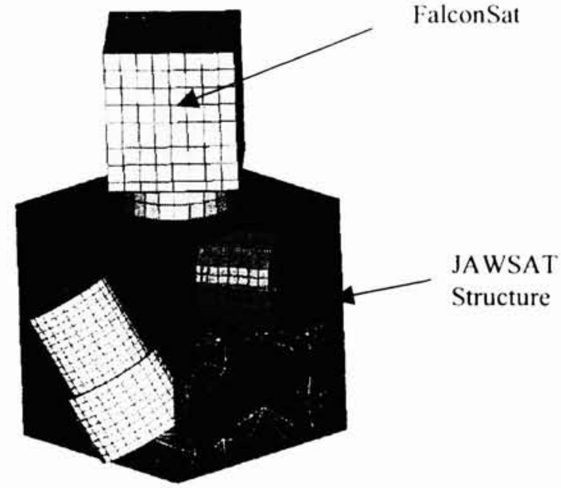

Figure 6. JAWSAT Configuration

The FalconSat deployment was a great success for the AFRL SMA mechanism programs in that it was the first time an AFRL device had been been launched in a non-experimental application. In addition, the QWKNUTs that were used operated reliably and incorporated all of the essential design features that represent improvements over traditional devices, such as low-shock, ability to reset, and safety.

5.0 LIGHTWEIGHT FLEXIBLE SOLAR ARRAY PROGRAM

The Lightweight Flexible Solar Array (LFSA) is a joint AFRL/DARPA/NASA/LMA program to develop innovative solar array technologies to meet the challenging power goal of >100 W/Kg for future Air Force and NASA missions. One element of the solar array technology development is investigation of SMA hinges for array deployment. The advantages of a SMA hinge over other hinges include controlled low-shock deployment, reduced noise and vibration, fewer parts, lightweight, higher reliability, and ease of production and assembly. The LFSA program provides three flight opportunities to demonstrate solar array deployment hinges and solar array panel deployment using the hinges.

Figure 7 shows an SMA hinge in the undeployed and deployed states. The hinge consists of two nitinol SMA strips with heating elements at both ends. When heated, each SMA strip recovers its parent shape to form the required configuration for the deployed arrays. The final deployed shape of the two strips incorporates opposing elliptical curvatures in the transverse direction to provide stiffness in the hinge.

The first LFSA experiment, designed by LMA, tested six SMA hinges on the Space Shuttle Columbia (STS-93) in July 1999. The experiment, shown in Figure 8, provided a way to test SMA hinges in a weightless environment prior to being applied to a future spacecraft design. The goal of the STS experiment was to test the ability of the SMA hinges to deploy completely and at the correct rate. The ability to design for a particular deployment rate is the key to controlling shock and providing a smooth deployment.

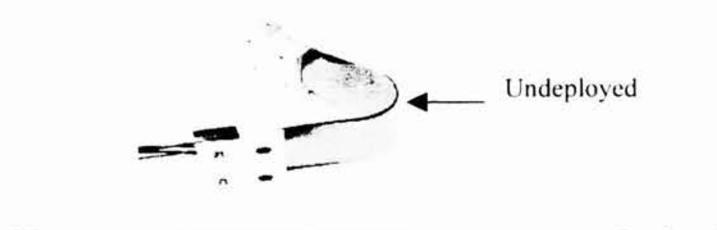

Figure 7. SMA Hinge in Deployed and Undeployed Configuration

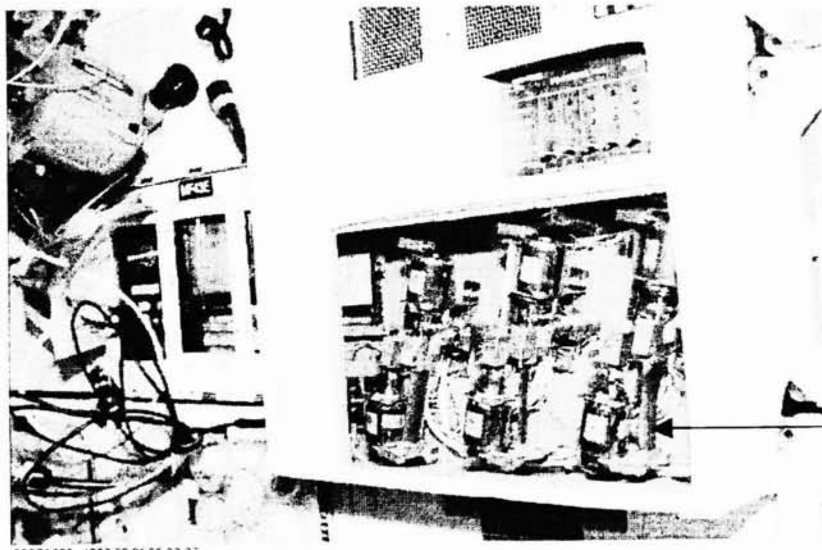

Figure 8. Shuttle Hinge Experiment

Three pairs of SMA hinges were flown in the STS-93 program. Each pair consisted of a full size and half size hinge. Full size is that required for the solar array. The two different sizes were included to assist in verification of a Finite Element model of the hinges. Hinges with different transition temperatures in the range of 50-60 C were tested. The third pair of hinges was in a "superelastic" state, which indicates that the material had transitioned at the ambient temperature of the experiment. The intent of including this superelastic pair was to simulate the condition where the hinge had been heated past the transition point prior to being released. In this case, when released, the hinge immediately reverts to the deployed state with no power required. This would be the worst case deployment scenario with regard to shock.

In the experiment, potentiometers were used to measure the displacement of the hinges over time as they were heated past the transition point into the deployed configuration. The temperature of the hinges was also recorded. All of the hinges deployed successfully through the intended range. Preliminary data analysis indicates that the deployment rates can meet the shock requirements for the solar array application.

The on-orbit success of the first experiment has provided substantial confidence in the hinges. The second of the LFSA experiments consists of two 20 cm by 50 cm solar array panels connected by two SMA hinges at the spacecraft and between the panels. This experiment, shown in Figure 9, will be launched on NASA's Earth Observer 1 (EO-1) in April 2000.

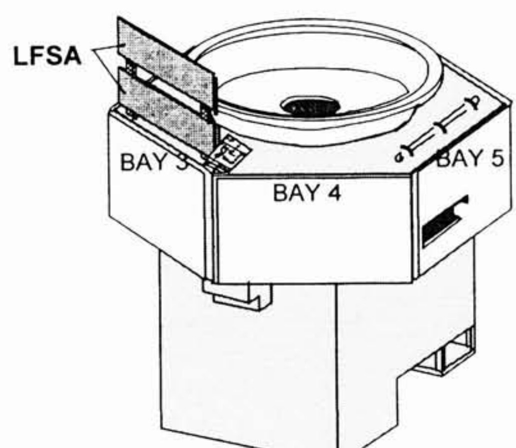

Figure 9. Earth Observer 1 Spacecraft

6.0 CONCLUSION

The first generation of new low-shock, SMA spacecraft mechanisms has been successfully designed and developed. Basic design goals such as low shock, simplicity, and compatibility with traditional device parameters have been met. The devices have undergone rigorous testing both on the ground and on-orbit, and have demonstrated that SMA devices meeting all satellite release requirements are available for upcoming launch endeavors. Flight successes represent the near term challenge, which is reliable performance on-orbit as part of a complete system, whether it be spacecraft separation or array deployment. In the future, smaller devices will be required as the size of satellites further decreases. Not only will low-shock be an issue but minimal intrusion in the satellite design will become even more critical because of extremely limited surface area and volume. The success of SMA devices in these applications may very well be the driver for incorporation of the devices in more traditional large scale systems, such as the separation systems commonly used for large satellites and fairings.

7.0 ACKNOWLEDGEMENTS

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